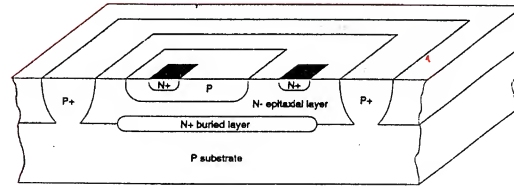
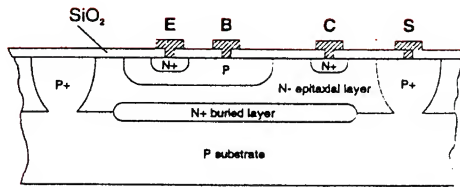
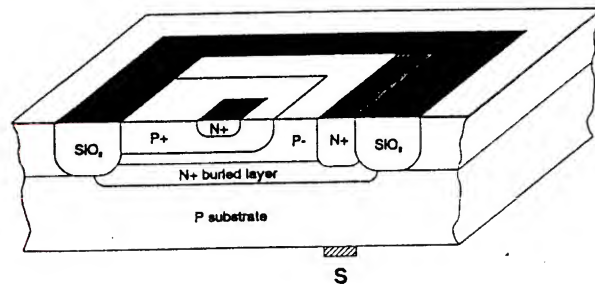
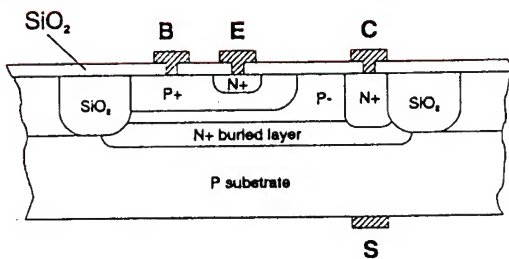


Chapter 3: Bipolar Junction Transistor

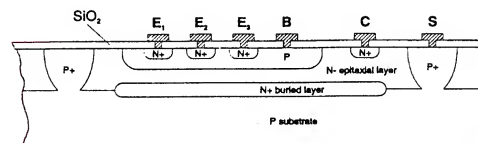
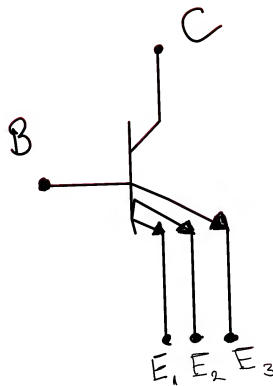
Junction isolated NPN BJT



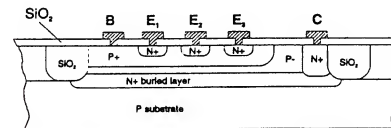
Oxide isolated NPN BJT



Multi-Emitter BJT



(a)

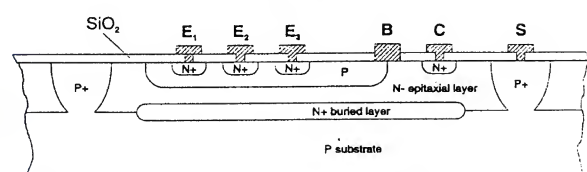
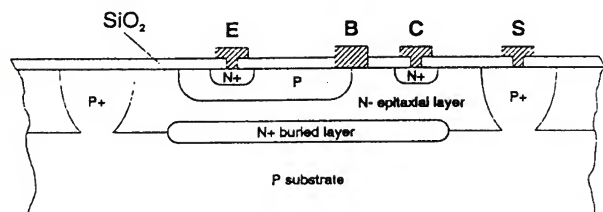


(b)

FIGURE 3.3 Multi-emitter NPN BJTs: (a) Junction isolation technology, (b) Oxide isolation technology

Schottky-clamped BJT

- * The base contact is extended over the N collector region which forms schottky diode in parallel with the base collector PN junction
- * Multi-emitter BJT converted to schottky clamped BJT's by placing schottky MN diode in parallel with the PN base-collector junction.

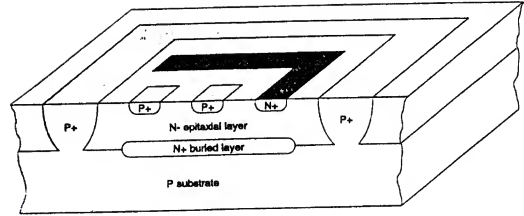


Lateral PNP BJT:

* Lateral PNP BJT is constructed from PNP BJTs along with NPN BJTs.

* Lateral PNP have much reduced β_f because the base width is about an order of magnitude larger than that of the NPN.

* β_f for the PNP is reduced due to uniform N base doping as well as reduced emitter carrier collection at the collector as compared with the NPN.



The Ebers-Moll BJT Model

* A simple model that represents the first order DC operation of BJT.

NPN BJT Model

$$I_{D, BE} = I_{ES} (e^{V_{BE}/\phi_T} - 1)$$

$$I_{D, BC}(V_{BC}) = I_{CS} (e^{V_{BC}/\phi_T} - 1)$$

$I_{ES} \equiv$ Base-emitter saturation current

$I_{CS} \equiv$ Base-collector saturation current

$$\alpha_F I_{D, BE} = \alpha_F I_{ES} (e^{V_{BE}/\phi_T} - 1)$$

$$\alpha_R I_{D, BC} = \alpha_R I_{CS} (e^{V_{BC}/\phi_T} - 1)$$

$\alpha_F \equiv$ common base forward current amplification factor

$\alpha_R \equiv$ common base reverse current amplification factor

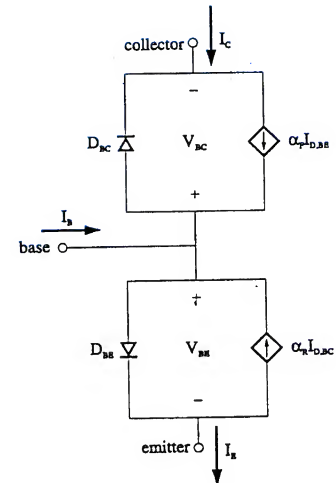
Typically $0 < \alpha_F < 1$

$$0.2 \leq \alpha_R \leq 0.6$$

$$I_E = I_{ES} (e^{V_{BE}/\phi_T} - 1) - \alpha_R I_{CS} (e^{V_{BC}/\phi_T} - 1)$$

$$I_C = \alpha_F I_{ES} (e^{V_{BE}/\phi_T} - 1) - I_{CS} (e^{V_{BC}/\phi_T} - 1)$$

$$I_E = I_B + I_C$$



Ebers-Moll NPN BJT Model

PNP BJT Model

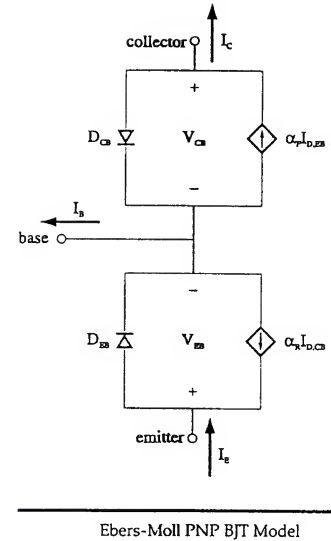
$$I_E = I_{D,EB} - \alpha_R I_{D,CB}$$

$$= I_{ES} (e^{V_{EB}/V_T} - 1) - \alpha_R I_{CS} (e^{V_{CB}/V_T} - 1)$$

$$I_C = \alpha_F I_{D,EB} - I_{D,CB}$$

$$= \alpha_F I_{ES} (e^{V_{EB}/V_T} - 1) - I_{CS} (e^{V_{CB}/V_T} - 1)$$

$$I_E = I_B + I_C$$



Reciprocity theorem

* I_{ES} , I_{CS} , α_F & α_R parameters are related by the reciprocity theorem for the ideal BJT.

$$\alpha_F I_{ES} = \alpha_R I_{CS} = I_S$$

BJT Modes of Operation

BJT Modes of Operation		
Base-Emitter PN Junction Bias	Base-Collector PN Junction Bias	Mode of Operation
Reverse	Reverse	Cutoff
Forward	Reverse	Forward active
Forward	Forward	Saturation
Reverse	Forward	Reverse active

Cut-off Mode

* Both PN junctions of the BJT are reverse biased

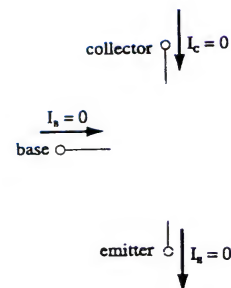
* $\therefore I_{D,BE}$ & $I_{D,BC}$ are zero. therefore $\alpha_F I_{D,BE} = \alpha_R I_{D,BC} = 0$.

$$I_{E(off)} = 0$$

$$I_{C(off)} = 0$$

* The actual currents are in the nanoamp range.

$$I_B = I_C = I_E \approx 0$$



Forward Active Mode.

$J_{BE} \Rightarrow$ Forward biased

$J_{BC} \Rightarrow$ Reverse biased.

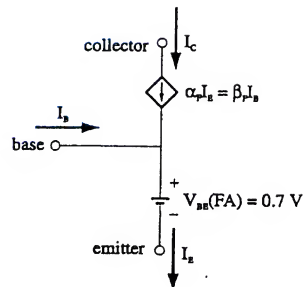
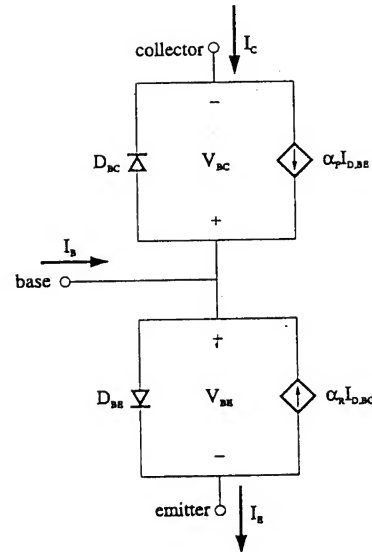


FIGURE 3.9 Reduced NPN BJT Model for the Forward Active Mode of Operation



Ebers-Moll NPN BJT Model

$$I_{D,BC} \approx 0$$

$$V_{BE(FA)} = 0.7V \quad (\text{for silicon diodes})$$

$$I_E = I_B + I_C$$

$$I_C(FA) = \alpha_F I_E$$

$$I_C(FA) = \beta_F I_B$$

$$\beta_F = \frac{\alpha_F}{1 - \alpha_F}$$

Saturation Mode.

- * Both J_{BE} & J_{BC} are forward biased.
- * In saturation mode I_C , I_E & I_B are larger than in other modes of operation
- * Due to larger currents $V_{BE} > [V_{BE(FA)} = 0.7]$

$$V_{BE(sat)} = 0.8V$$

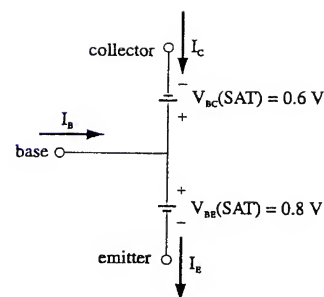


FIGURE 3.10 Reduced NPN BJT Model for the Saturated Mode of Operation

* Due to lighter doping V_{BC} will typically not exceed:

$$V_{BC}(sat) = 0.6V$$

* Due to V_{BE} & V_{BC} values:

$$V_{CE}(sat) = 0.2V$$

* A saturation parameter σ indicates the relationship between I_C & I_B and its defined as

$$\sigma = \frac{I_C}{\beta_F I_B}, \quad \sigma \leq 1$$

* $\sigma = 1$ means FA operation and/or edge of saturation operation

Reverse Active Mode

J_{BE} is reverse biased

J_{BC} is forward biased

$$V_{BC}(RA) = 0.7V$$

$$I_E(RA) = \alpha_R I_C = -\beta_R I_B < 0$$

$$\beta_R \ll \beta_F$$

$$\beta_R = \frac{\alpha_R}{1 - \alpha_R}$$

Family of Curves

- * For equal increments in I_B the curves in the active regions are approximately evenly spaced.
- * Curves in RA region are much closer together than those in FA region
- * Ebers-Moll predicts that β_F & β_R are independent of the terminal current magnitudes but this is not entirely true.

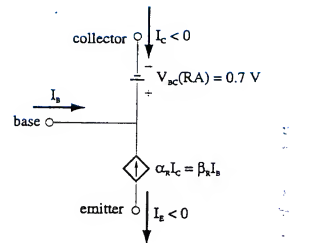
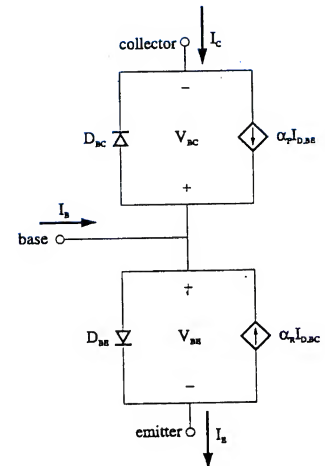
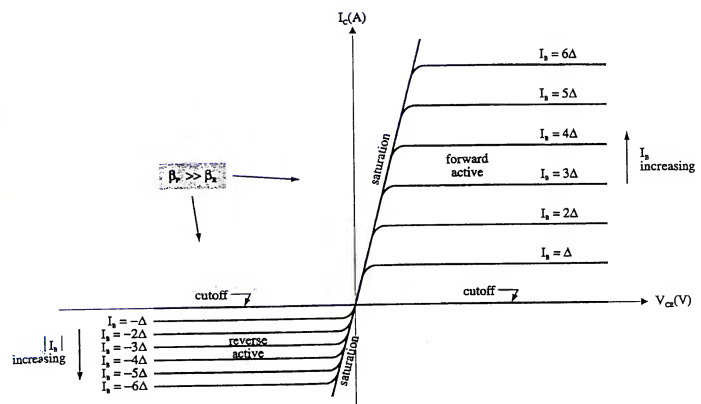


FIGURE 3.11 Reduced NPN BJT Model for the Reverse Active Mode of Operation



Ebers-Moll NPN BJT Model



The Gummel-Poon BJT Model

- * This model considers several second-order effects some of these are:
 - The early effect (base-width modulation)
 - The Sah-Noyce-Shockley effect
 - The Kirk effect (base width widening)

The Early Effect (Base-Width Modulation)

- * I_C vs V_{CE} curves obtained from the Ebers-Moll model shows no dependence of I_C on V_{CE} but there is a dependence observed due to early effect and its obvious on Gummel-Poon model curves.
- * The slopes of I_C vs V_{CE} increase as I_B increases
- * When the linear portion of the curves are extrapolated on the negative V_{CE} axis they intersect at a common voltage $-V_A$
- * $V_A \equiv$ Early voltage
- * The early effect is also present in the reverse active mode.

$$I_C = I_S \left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}} \right) \left(1 - \frac{V_{BC}}{V_A} \right) - \frac{I_S}{\beta_R} \left(e^{\frac{V_{BC}}{V_T}} - 1 \right)$$

$$I_B = \frac{I_S}{\beta_F} \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) + \frac{I_S}{\beta_R} \left(e^{\frac{V_{BC}}{V_T}} - 1 \right)$$

$$I_E = I_B + I_C$$

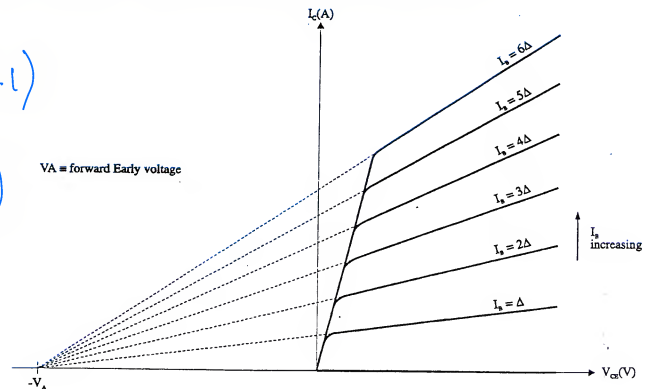


FIGURE 3.13 V_{CE} Dependence on I_C due to the Early Effect

The Kirk Effect (Base Width Widening)

- * Electronic devices and integrated circuit 2nd edition by Ajay Kumar Singh
- * Semiconductor Device Physics and Design by Umesh K. Mishra & Jasprit Singh
- * When the minority carrier concentration across the base-collector junction increases the electron concentration becomes comparable to the doping density of the collector. This has the effect of widening the base region & reducing the injected minority carriers that reach the collector and therefore β_F is reduced.

Low Current Level Depletion Layer Recombination

In BJT the depletion layer recombination increases the base current and therefore decreases the current gain.

$$I_D = I_S \left(e^{\frac{V_D}{N V_T}} - 1 \right)$$

SPICE BJT Model

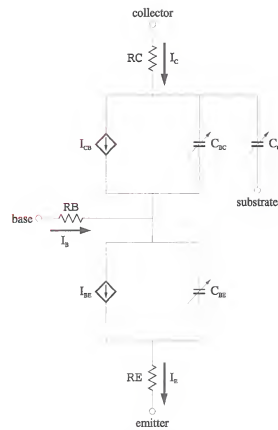


FIGURE 3.14 SPICE BJT Model (Modified Gummel-Poon model)

Integrated circuit resistors

- * TTL & ECL families continue to use IC resistors.

Ideal Rectangular Resistor.

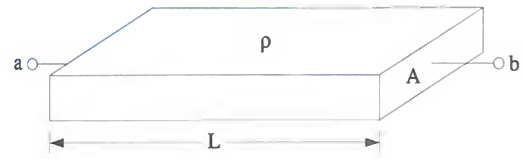
$$R_{ab} = \rho \frac{L}{A}$$

where:

ρ \equiv constant of resistivity

L \equiv Length.

A \equiv cross-section area.



Diffused Base Resistor

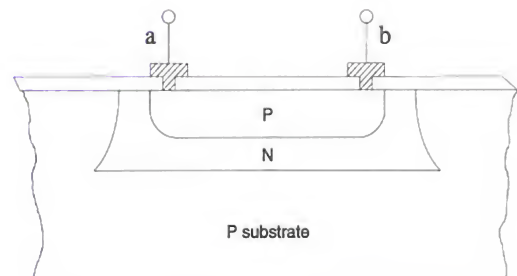
- * Using the base diffusion/implant region

$$R_{ab} = \rho_{SB} \frac{L}{W}$$

ρ_{SB} \equiv sheet resistivity

- * ρ_{SB} of this region is comparatively large and is useful for large IC resistors.

- * Typically $\rho_{SB} = 200 \Omega/\text{square}$.



$$\rho_{SB} = \frac{\rho}{t}$$

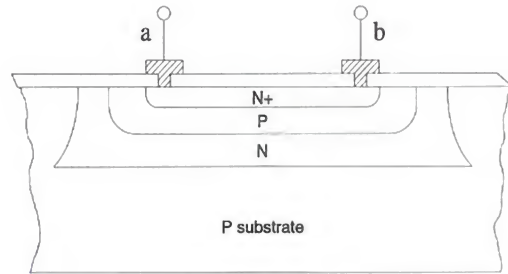
t \equiv thickness

Diffused Emitter Resistor

- * Using the emitter N^+ region for the resistor

$$R_{ab} = \rho_{SE} \frac{L}{W}$$

- * Typically $\rho_{SE} = 2 \Omega/\text{square}$.
- * This resistor used for small valued resistors



Pinch Resistor

- * Because the cross section of the pinch resistor has been reduced by N^+ diffusion. It has the largest value of resistance for a fixed length/width ratio of any of the IC resistors.
- * The reduced cross-section has the effect of increasing the sheet resistivity and hence resistor value.

$$R_{ab} = \rho'_{SB} \frac{L}{W}$$

